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# Planting date effects on flowering, seed yield, and oil content of rape and crambe cultivars

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**Abstract**

Both crambe (*Crambe abyssinicia*, Hochst) and rape (*Brassica napus* L. and *Brassica rapus* L.) are cool season crops, thus they may have potential as irrigated, winter rotational crops in the low deserts of the southwestern United States and northern Mexico. Currently, no information is available on the effects of fall planting date on the production of these crops. The objectives of this study were (1) to determine the effects of fall planting date on flowering patterns, seed yield, and oil content of crambe and two species of rape, and (2) to determine the suitability of rape and crambe as rotational crops for the low deserts of the southwestern United States. Nine cultivars of rape and one cultivar of crambe were planted at the Maricopa Agricultural Center on three dates in November and December of 1995 and four dates from October through December of 1997 on a variable Mohall sandy loam soil (fine-loamy, mixed hyperthermic, Typic Haplargid). Five of the rape cultivars were *B. napus* types and the remaining four were *B. rapus*. One was an industrial rape (R-500) and the other eight were Canola types. Seed yield, oil concentration, and seed weight were determined. In 1996, the percent of plants flowering was observed visually on a periodic basis. In 1998, detailed imaging of flowering was done periodically using a digital camera. Planting date affected water application by controlling the length of the growing season. Our plants were taller, oil content was higher, seed weights were comparable, days to flowering were more than doubled, and seed yields were lower than plants from spring plantings in the Northern Great Plains. In both years of the study, the highest yields were obtained when rape and crambe were planted in November, which would fit well with cotton harvest dates. Lodging was a serious problem in rape. Crambe was sensitive to frost and could fail in some years. Only R-500 matured early enough to be used in rotation with current cotton cultivars. In addition to the onset of flowering, the automated method for estimating flowering was able to detect differences between Brassica species and cultivars and to measure the duration of flowering. Each species had a distinctive flowering pattern. Planting dates also affected the pattern and efficiency of flowering. Reproductive efficiency appeared to change with planting date and in general, October and November planting dates produced seed with higher oil content and seed weights than December planting dates.
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## 1. Introduction

Rape has been grown as an oil crop for both edible and industrial uses. Primarily, two species of rape have

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been cultivated, *Brassica napus* L. and *Brassica rapus* L. (Busch et al., 1994). The edible form of the oil is marketed as Canola oil and is used in margarine, salad dressings, and other edible applications. When grown for industrial oil, the oil has a high erucic acid content and has been used for lubricants and as a diesel fuel replacement. Crambe (*Crambe abyssinicia*, Hochst) has also been developed as a source of erucic acid (Johnson et al., 1995), which is used in the plastic industry.

Traditionally, rape and crambe have been grown in the northern Great Plains of the United States and Canada, and northern Europe. Since its introduction, the production range of Canola has expanded to include the Intermountain Northwest and the southeastern portions of the United States. Because both crambe and rape are cool season crops, they may have potential as winter rotational crops in a continuous cropping system for the desert southwest of the United States. Continuous cropping systems have the potential to reduce groundwater contamination by nitrate.

An important management factor in the production of all crops is planting date. Planting date is critical in cold climates due to the potential for frost damage both early and late in the season in rape and crambe cultivation (Gross, 1964; Kondra, 1977; Johnson et al., 1995). Johnson et al. (1995) showed that high temperatures at the end of the growing season can also reduce yields, and more recently, Morrison and Stewart (2002) observed that flowering of rape is inhibited above 27 °C. Therefore, in the desert southwest, planting date may be important to avoid high temperatures at the end of the growing season.

Flowering is the initial visual indication of the reproductive potential or yield of plants. However, counting flowers manually can be labor intensive and cost prohibitive for many research projects. Manual counts of flowers can lead to plot and plant damage, thus making resulting yield and quality factor determinations from these plots questionable. Flower counts are useful to breeders and plant physiologists in determining the reproductive efficiency of plants. Flowering can influence yield increases in two ways (Coffelt et al., 1989). First, the number of flowers per plant can be increased which can result in increased yield. Second, the percentage of flowers producing fruit can be increased that also results in increased yield. A knowledge of the process responsible for increased yields in specific germplasm lines is necessary for developing breeding strategies to further increase yields. Determining peak flowering for indeterminant crops, such as crambe and rape, can also be helpful in predicting optimum harvest dates. Flowering information is also useful to plant growth modelers in predicting yield potential and maturity dates.

Recently, Adamsen et al. (2000) developed a non-destructive method for counting flowers using a digital camera. This method eliminated traffic into the plots for flower counts. The procedure allowed the same area of the plot to be monitored repeatedly throughout the growing season. In addition, this method was used to determine the effects of plant population and fertility level on the flowering and subsequent yield of lesquerella [*Lesquerella fendleri* (Gray) Wats] (Adamsen et al., 2003). Currently, no information is available on the effects of planting date on the flowering of rape and crambe grown in the low deserts of the southwestern United States and northern Mexico. The objectives of this study were to determine (1) the effects of fall planting date on flowering patterns, seed yield, and oil content of two Brassica species and crambe, and (2) the suitability of irrigated rape and crambe as winter rotational crops in a continuous cropping system with cotton for the low deserts of the southwestern United States.

## 2. Materials and methods

Nine cultivars of rape and one cultivar of crambe (cv. Meyer) were planted at the Maricopa Agricultural Center (latitude 33.07°, longitude 111.98°), 40 km south of Phoenix, Arizona, in 1995 on 3 November, 24 November, and 15 December, and in 1997 on 21 October, 5 November, 21 November, and 17 December. Five of the rape cultivars were *B. napus* types (A112, Cyclone, Oscar, ST-011, and Westar) and the remaining four were *B. rapus* types (CSU-045, Hyola-029, R-500, and Tobin). R-500 is an industrial rape and the others are edible or Canola types. Plots were eight rows planted on 0.25 m centers and 10 m long. The soil was a variable Mohall sandy loam (fine-loamy, mixed hyperthermic, Typic Haplargid) (Nelson et al., 1996). No pesticide applications were made. Fertilizer nitrogen was applied preplant at a rate of 56 kg $ha^{-1}$, and an additional 56 kg $ha^{-1}$ was applied at the begin-

Table 1
Number of irrigations, amounts of irrigation water and rainfall applied to rape and crambe, and cumulative reference evapotranspiration ($CET_0$) during the crop years 1995–1996 and 1997–1998

| 1995–1996 | | | | | | 1997–1998 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date of planting | Number of irrigations | Cumulative $ET_0$ (mm) | Irrigation (mm) | Rainfall (mm) | Total (mm) | Date of planting | Number of irrigations | Cumualtive $ET_0$ (mm) | Irrigation (mm) | Rainfall (mm) | Total (mm) |
| 3 November | 8 | 655 | 636 | 33 | 669 | 21 October | 4 | 607 | 295 | 143 | 438 |
| 24 November | 7 | 642 | 578 | 33 | 611 | 5 November | 4 | 557 | 274 | 143 | 417 |
| 15 December | 6 | 596 | 504 | 33 | 537 | 21 November | 4 | 529 | 218 | 141 | 359 |
| | | | | | | 17 December | 5 | 564 | 305 | 117 | 422 |

ning of flowering. In 1996, 168 kg $ha^{-1}$ and in 1998, 56 kg $ha^{-1}$ of N were applied during seed-fill. All nitrogen fertilizer was applied as ammonium sulfate. Fertilizer amounts were based on pre-plant soil samples and recommendations of the University of Idaho Extension Service (Mahler and Guy, 2002).

The crop was sprinkler irrigated for stand establishment and then flood irrigated for the remainder of the growing season (Table 1). After stand establishment, irrigation times and amounts were determined using the irrigation scheduling program AZSCHED with the crop coefficients for wheat developed for Arizona (Fox et al., 1993). Each planting date was scheduled independently from the others and irrigations were made when soil depletion was estimated to be at or near 50% of the available water based on the weather and crop conditions. Modeled soil moisture levels were confirmed with soil moisture estimates made using a combination of neutron scattering and time domain reflectance measurements. Weather data from the AZMET weather station at the Maricopa Agricultural Center (Yitayew and Brown, 1990) were used as inputs for the irrigation scheduling model. In addition, AZMET air temperature data were used to compute the growing-degree-days (GDD) from planting to flowering in both years for each planting date cultivar combination. Daily growing-degree-days (DGDD) were calculated using a base temperature (BT) of 0 °C and the formula DGDD = mdat − BT, where mdat is the mean daily air temperature in °C. DGDD values were summed from planting to flowering for each planting date-cultivar combination to obtain GDD.

During the 1995–1996 growing season, the percentage of plants that were flowering was estimated visually from 16 January 1996, the beginning of flowering for the earliest 1995 planting date, through 26 March 1996, the end of flowering for the latest 1995 planting date in order to obtain an estimate of flowering duration. During the 1997–1998 growing season, flowering duration and intensity were estimated from digital images of the flowers taken periodically from 29 January 1998, the beginning of flowering for the 21 October 1997 planting date, through 16 April 1998, the end of flowering for the 17 December 1997 planting date, using an auto-focusing, color digital camera with an *f*2.8, 5 mm lens (Model D300L, Olympus America Inc., Melville, NY). The camera's nominal field of view was 57 by 42°. The camera was positioned at a constant 1.6 m above the top of the plant canopy and the position adjusted as necessary with crop growth. The camera was extended 1 m into the plot to avoid edge effects. This was accomplished by mounting the camera to an arm attached perpendicular to a telescoping pole that could be extended to a maximum height of 6 m. Thus, the same area could be imaged each time without physical entry into the plots. When images were taken, the pole was maintained in a vertical position so the camera always had a nadir view of the plot. The area selected for imaging in each plot was chosen to be representative of the plot on 29 January 1998, the first date the images were taken. Images were acquired between 1030 and 1300 h MST. The camera's built-in flash was used for each image. A white plate with red, green, and blue strips was included at the edge of each scene to provide color balance and brightness control.

An estimate of flowering intensity in a 1 $m^2$ area in each image was made by identifying all of the pixels that were flowers (Adamsen et al., 2000). Images were cropped to show only 1 m × 1 m. This reduced the field of view to 36°. Flower pixel identification was accomplished by finding all pixels with red and green values above a threshold. The white pixels were then excluded and the remaining pixels were accepted as flower pixels. The following modifications were made to the original method. The image processing was carried out with an updated version of MatLab (5.1.3.29215a [R11.1], MathWorks Inc., Natick, MA), which can read the JPEG (joint photographic experts group) files produced by the camera. This eliminated the preprocessing step of converting the image from JPEG format to GIF (graphic interchange file) format. The threshold value for the red (R) and green (G) numbers used to define a flower was increased from 85% of maximum previously used by Adamsen et al. (2000) to 95%. For crambe, which has white flowers rather than yellow, all of the steps involving searches for yellow pixels were eliminated. The percent flower pixels in an image was used as a measure of flowering intensity rather than estimating the number of flowers in the 1 $m^{-2}$ area. Total flowering was calculated as the sum of flower pixels for all dates for a cultivar within a planting date. Peak flowering was when the maximum percent of flower pixels for a cultivar within a planting date was reached.

The heights of three randomly chosen plants in each plot were measured weekly. Individual cultivars were harvested when they matured. A cultivar was determined to be mature when flowering had ceased and all of the pods had begun to turn brown (Gross, 1964). In 1995–1996, a 1.5 m length of the center four rows in each plot was hand cut for yield. In 1997–1998, a 1 m length of the center four rows of each plot that corresponded to the 1 $m^2$ area that was imaged during the growing season was hand cut for yield. After cutting, plant material was dried in windrows for 7–10 days and then thrashed. While the area used for the yield estimate was smaller in 1997–1998 than in 1995–1996, it allowed direct comparison of yields with the flower index developed for each cultivar. Hand harvesting and thrashing allowed the inclusion of lodged plants in the yield estimates. Yields are reported as dry weight of seeds. One thousand, clean, mature seed were hand counted and weighed to determine 1000 seed weights. Three grams of mature clean seed were used to determine seed oil content. Total seed oil was measured using a calibrated QP20 Pulsed NMR Analyzer (Oxoford Instruments Corp., Concord, Massachusetts, USA). Total seed oil content was expressed as a percentage of dry mass as calculated by the instrument.

The experimental design was a randomized complete block split plot design with three replications. Main effects included planting dates as whole plots and cultivars as split plots. Seed yield, 1000 seed weight, and oil content data were subjected to statistical analyses using the GLM procedure (general linear model) of SAS for personal computers (SAS Institute, 1987). Years were analyzed separately because the year by cultivar and year by planting date interactions were significant ($P < 0.05$). Regression analyses of peak flowering and total flowering with yield were made using the built in statistical functions of Microsoft Excel 2000 (Microsoft Corp, Redmond, WA). These regression analyses were done for each cultivar including crambe across planting dates and for each planting date across all rape cultivars. Crambe was excluded from the within planting date regressions because the number of flower pixels between crambe and rape were not comparable.

## 3. Results and discussion

While there were differences in temperature and rainfall between the two growing seasons of the study, they were typical growing seasons for the area. The 1995–1996 growing season was warmer and drier than 1997–1998 (Table 1, Fig. 1). In 1995–1996, a total of 33 mm of rain fell during 3 days of rain spread over the growing season. In 1997–1998, 143 mm of rain fell over 26 days. The greater number of rainy days and the associated cloudiness in 1997–1998 compared with 1995–1996 also resulted in lower evapotranspiration in 1997–1998 than 1995–1996. The cumulative reference evapotranspiration ($ET_0$) as reported by the AZMET weather system for the Maricopa Agricultural Center (Yitayew and Brown, 1990) in 1997–1998 ranged from 607 mm for the 21 October planting date to 529 mm for the 21 November planting date, whereas in 1995–1996, the cumulative $ET_0$ was between 655 mm for the 3 November planting date and 596 mm for the 15 December planting date (Table 1). The differences in cumulative $ET_0$ corresponded well with the differences in water applied within years, but indicate that the crop may have been over-irrigated early in the 1995–1996 growing season. In addition to the water applied using sprinkler irrigation for stand establishment, water was applied by flood irrigation six to eight

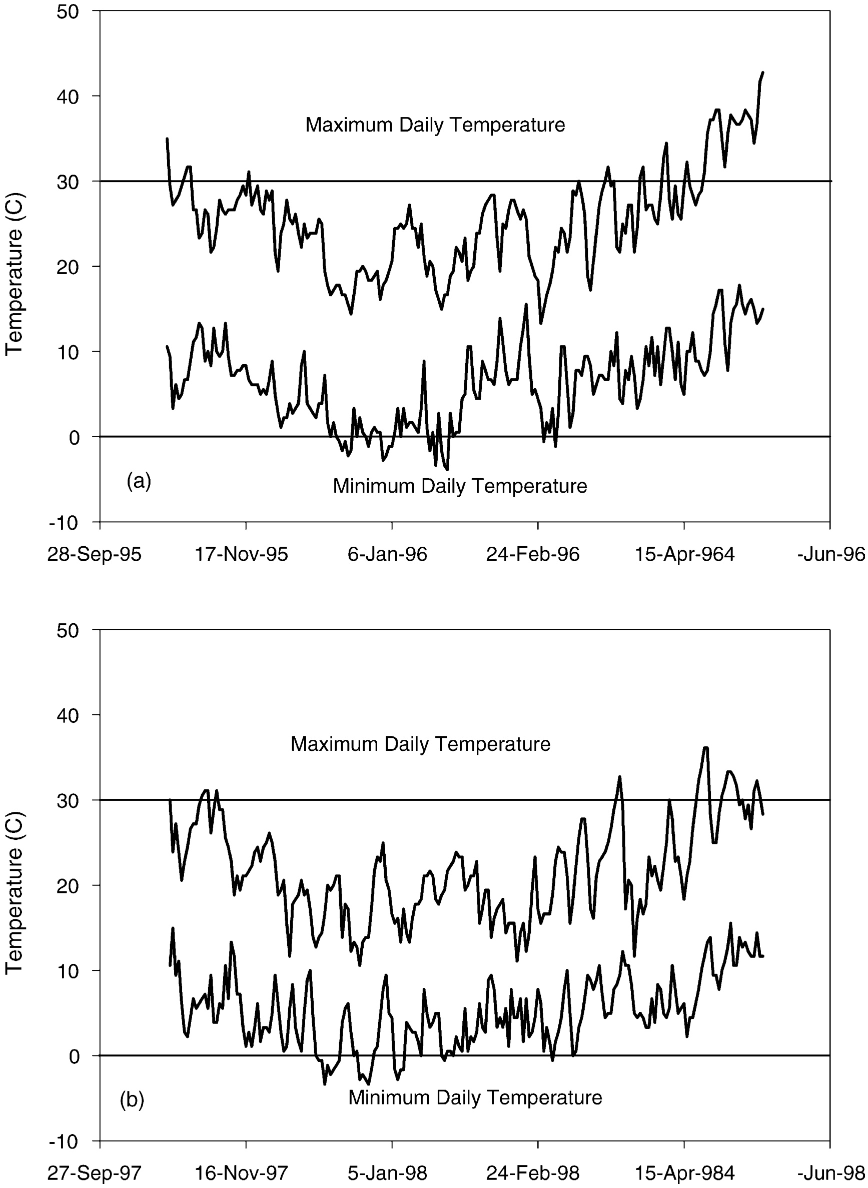


Fig. 1. Maximum and minimum air temperatures for crambe and rape in the (a) 1995–1996 and (b) 1997–1998 growing seasons.

times in 1995–1996 (Table 1). Due to the frequency and timeliness of rainfall, the number of surface irrigations was only 4–5 in 1997–1998.

Flowering behavior among the *B. rapus* cultivars (CSU-045, Hyola-029, R-500, and Tobin) was similar. Therefore, the time to flowering was averaged over all *B. rapus* cultivars (Table 2) and only data for Hyola-029 and Tobin are shown graphically (Figs. 2–4). Similarly for the *B. napus* cultivars (A-112, Cyclone, Oscar, ST-011, and Westar) time to flowering was averaged over *B. napus* cultivars (Table 2) and only the data for A-112 and Oscar are shown graphically (Figs. 2–4). For crambe and the *B. rapus* cultivars, flowering occurred 20 days sooner in 1995–1996 than the comparable planting dates in 1997–1998, and approximately 10 days sooner in

Table 2
Dates of planting, start of flowering, and end of flowering, days to flowering and days of flowering, and growing-degree-days (base 0 °C) from planting to flowering for crambe, the average of the *Brassica rapus* culitvars (CSU-045, Hyola-029, R-500, and Tobin), and the average of the *Brassica napus* cultivars (A-112, Cyclone, Oscar, ST-011, and Westar) in the 1995–1996 and 1997–1998 growing seasons

| Species | Date of planting | Start of flowering | Days to flowering | Growing-degree-days | End of flowering | Days of flowering |
|---|---|---|---|---|---|---|
| 1995–1996 | | | | | | |
| Crambe | 3 November 1995 | 26 January 1996 | 84 | 1103 | 5 March 1996 | 39 |
| | 24 November 1995 | 20 February 1996 | 88 | 1122 | 13 March 1996 | 22 |
| | 15 December 1995 | 3 March 1996 | 79 | 957 | 26 March 1996 | 23 |
| *B. rapus* | 3 November 1995 | 16 January 1996 | 74 | 1011 | 5 March 1996 | 49 |
| | 24 November 1995 | 6 February 1996 | 74 | 880 | 13 March 1996 | 36 |
| | 15 December 1995 | 20 February 1996 | 67 | 817 | 26 March 1996 | 35 |
| *B. napus* | 3 November 1995 | 12 February 1996 | 101 | 1352 | 5 March 1996 | 22 |
| | 24 November 1995 | 20 February 1996 | 88 | 1122 | 13 March 1996 | 22 |
| | 15 December 1995 | 3 March 1996 | 79 | 957 | 26 March 1996 | 23 |
| 1997–1998 | | | | | | |
| Crambe | 21 October 1997 | 29 January 1998 | 100 | 1221 | 19 March 1998 | 49 |
| | 5 November 1997 | 13 February 1998 | 100 | 1136 | 27 March 1998 | 42 |
| | 21 November 1997 | 5 March 1998 | 104 | 1113 | 9 April 1998 | 35 |
| | 17 December 1997 | 19 March 1998 | 92 | 1025 | 16 April 1998 | 28 |
| *B. rapus* | 21 October 1997 | 29 January 1998 | 100 | 1221 | 19 March 1998 | 49 |
| | 5 November 1997 | 6 February 1998 | 93 | 1056 | 27 March 1998 | 49 |
| | 21 November 1997 | 23 February 1998 | 94 | 996 | 3 April 1998 | 39 |
| | 17 December 1997 | 12 March 1998 | 85 | 922 | 16 April 1998 | 35 |
| *B. napus* | 21 October 1997 | 13 February 1998 | 115 | 1392 | 19 March 1998 | 34 |
| | 5 November 1997 | 23 February 1998 | 110 | 1236 | 27 March 1998 | 32 |
| | 21 November 1997 | 5 March 1998 | 104 | 1113 | 9 April 1998 | 35 |
| | 17 December 1997 | 19 March 1998 | 92 | 1025 | 16 April 1998 | 34 |

1995–1996 than 1997–1998 for the *B. napus* cultivars (Table 2).

The differences between years are most likely the result of warmer conditions in 1995–1996 than in 1997–1998 (Fig. 1), which led to more rapid development of the crop in 1995–1996 than in 1997–1998. The *B. rapus* cultivars always began flowering first, followed by the *B. napus* cultivars. In early planting dates, crambe began flowering at about the same time as the *B. rapus* cultivars, but by the latest planting date, crambe began flowering about the same time as the *B. napus* cultivars. The number of days from planting to flowering for crambe averaged 86 days in 1995–1996 for the November planting dates and decreased to 79 days for the December planting date. In 1997–1998, the days to flowering for crambe was about 100 days for the October and November planting dates and then decreased to 92 days for the December planting date (Table 2). For the Brassica species, the number of days to flowering from planting tended to decrease with later planting. Under the conditions of this experiment, the days from planting to first flowering were much longer than those reported for the spring planted trials (Gross, 1964; Johnson et al., 1995; Kmec et al., 1998).

Although the days to flowering seemed to respond to temperature differences between the 2 years, the development rates of the fall planted rape and crambe were not the same as when spring planted in the Northern Great Plains. The decrease in days to flowering in the later planting dates compared with the earlier planting dates cannot be explained by temperature alone. Attempts to apply growing-degree-days to explain flowering behavior were not successful (Table 2). In general, the growing-degree-days between planting and flowering decreased as planting was delayed indicating that other factors such as photoperiod may be responsible for the initiation of flowering.

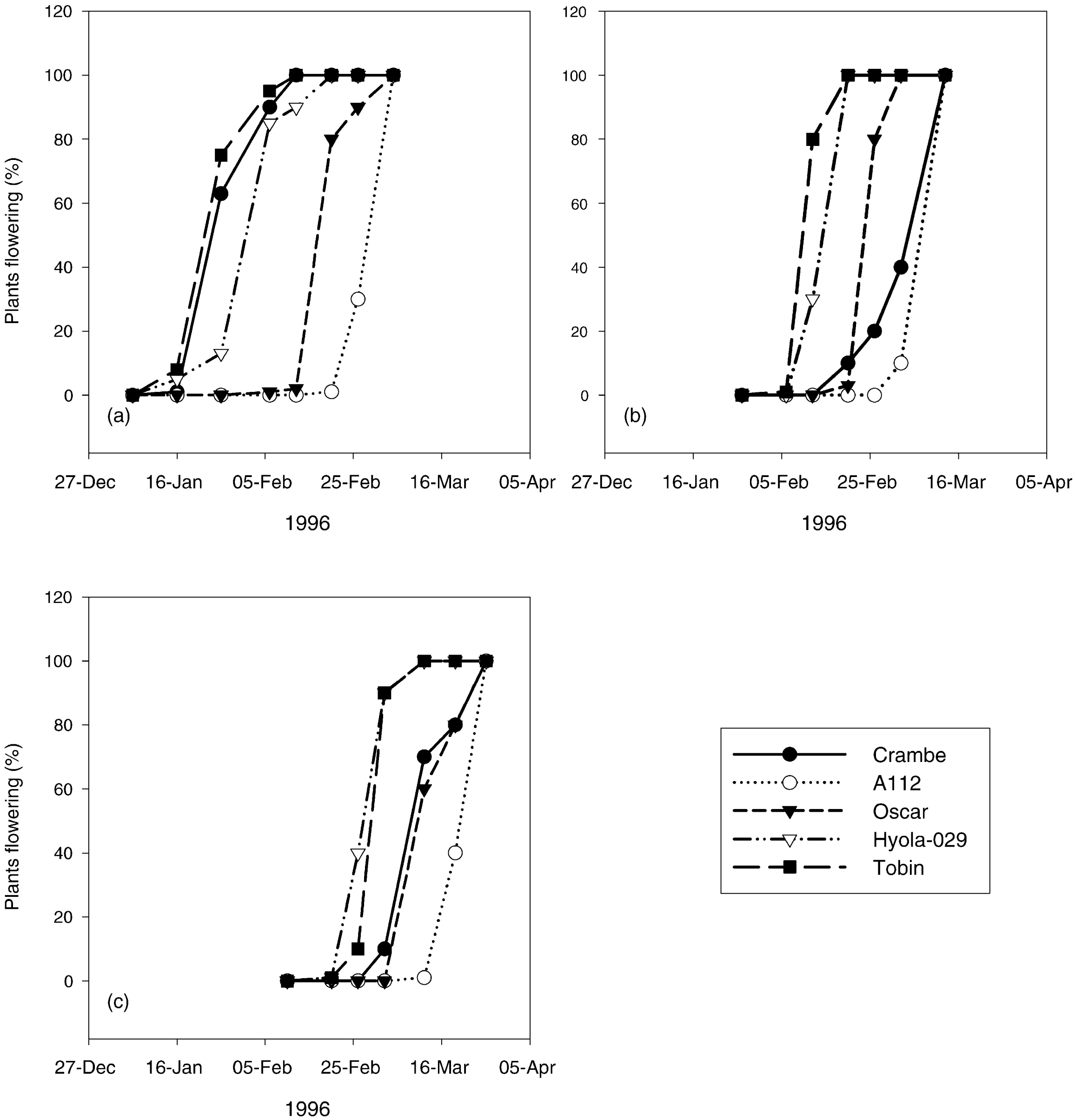


Fig. 2. Flowering of selected rape cultivars and crambe planted on (a) 3 November 1995, (b) 24 November 1995, and (c) 15 December 1995.

The visual estimates of flowering in 1995–1996 did not provide information on flowering intensity (Fig. 2). All of the plants had some flowers almost up to harvest, which led to an exaggerated estimation of total flowering with this method. The use of flower count estimates as represented by the percent flower pixels in an image in 1997–1998 allowed more accurate estimation of the start, duration, and sum of flowering (Table 2, Figs. 3 and 4). When observations of flowering were first taken in both years of the study, not all of the cultivars were in flower. When digital images were used in 1997–1998 to estimate flowering intensity, fully illuminated and brightly lit leaves at the top of the plants led to a large number of false

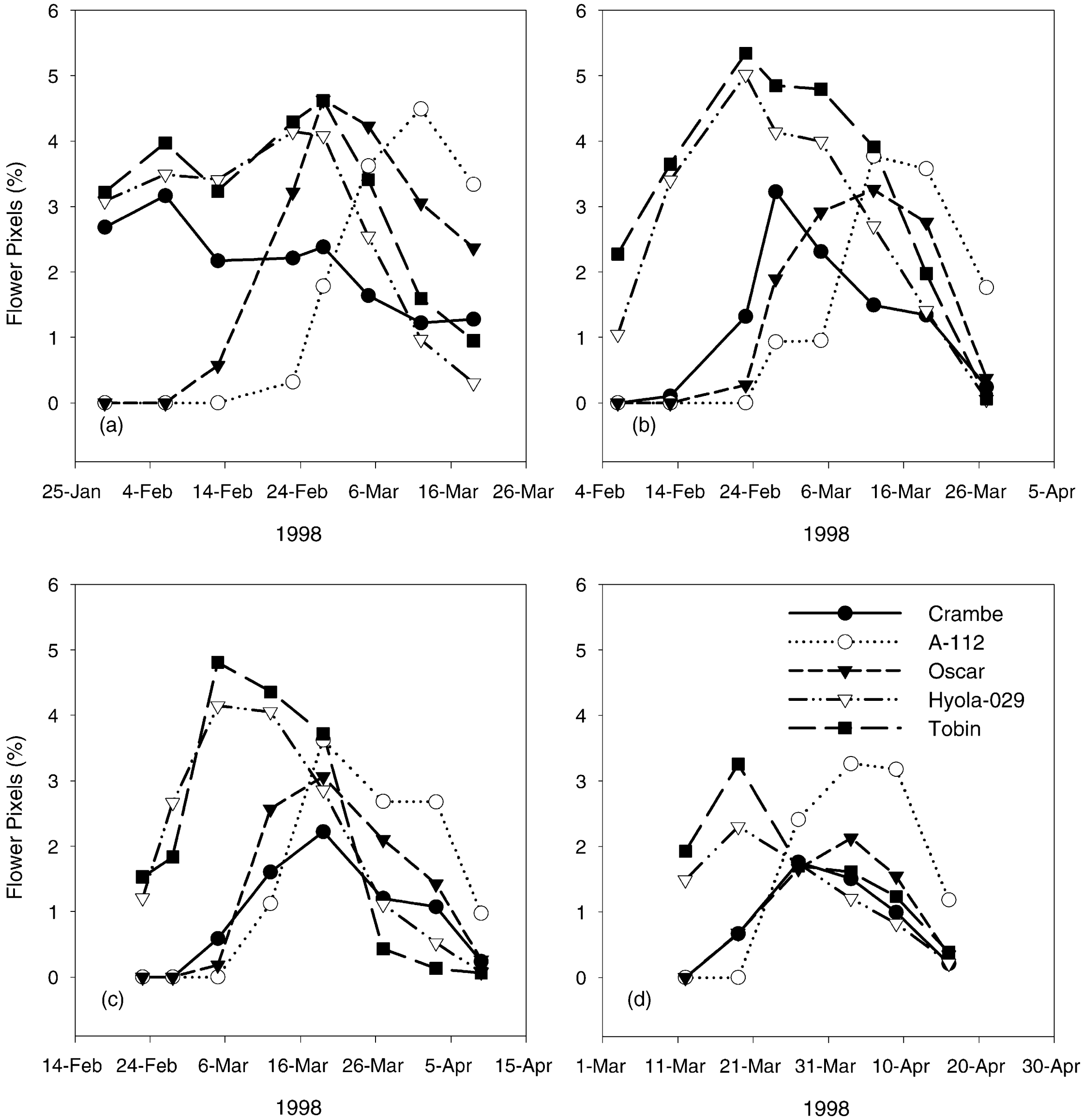


Fig. 3. Flowering of selected rape cultivars and crambe planted on (a) 21 October 1997, (b) 5 November 1997, (c) 21 November 1997, and (d) 17 December 1997.

positives in flower pixel estimates. To correct for this phenomena, we manually forced all of the scenes with no flowers to zero. Once flowering started, the flower stalks were above the leaves and the problem of false positives disappeared. Because flowering observations in 1995–1996 were visual estimates of the percentage of plants with flowers, false positives were not a problem.

None of the species showed a peak in flowering following irrigation events similar to those reported for lesquerella by Adamsen et al. (2003). The maximum percent of flower pixels in crambe was lower than that for any of the rape cultivars (Fig. 2). Crambe flowers are much smaller than rape flowers, but much more numerous. In rape, each flower that produces seed results in a pod with multiple seeds, whereas crambe

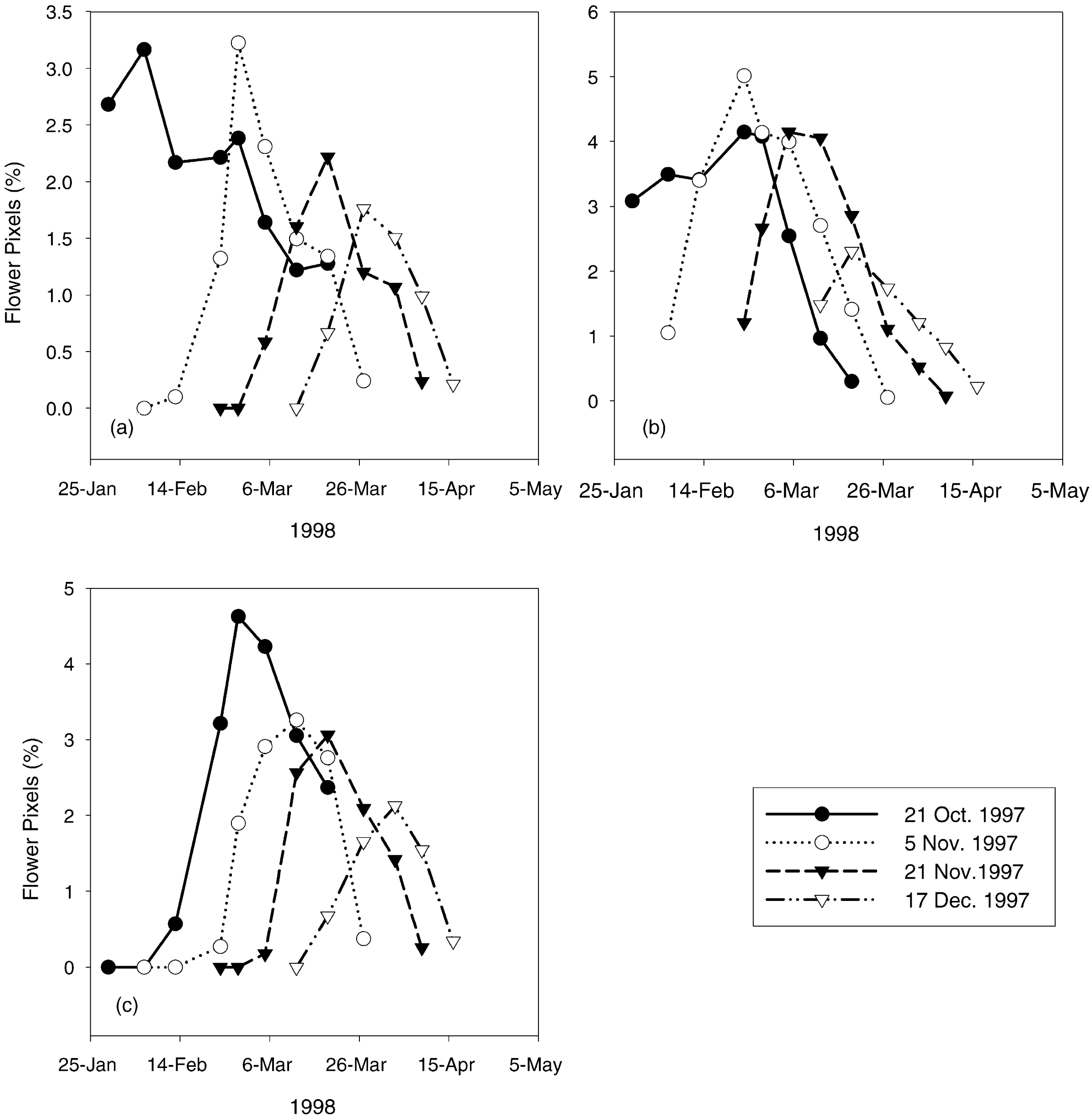


Fig. 4. Flowering of (a) crambe, (b) Hyola-029, and (c) Oscar for all planting dates during the 1997–1998 growing season.

flowers produce a single seed from each flower. As a result, the percent of flower pixels for crambe is not directly comparable with the percent flower pixels for the Brassica species. Crambe flowering duration decreased from seven to four weeks for the 21 October to 17 December planting dates, respectively (Table 2). For the *B. rapus* cultivars, flowering lasted for seven weeks for the 21 October and 5 November planting dates, and decreased to five weeks for the 17 December planting date. In contrast, the duration of flowering for the *B. napus* cultivars was relatively constant at about five weeks (Table 2). The visual estimates of flowering made during the 1995–1996 growing season indicated differences in the initiation of flowering between the Brassica species, and between the Brassica species and crambe (Fig. 2). The differences among

Table 3
Mean squares from analyses of variance for yield, oil content, and 1000 seed weight of rape and crambe cultivars for the 1995–1996 and 1997–1998 crop years

| | 1995–1996 | | | | 1997–1998 | | | |
|---|---|---|---|---|---|---|---|---|
| | d.f. | Seed yield | 1000 seed weight | Oil concentration | d.f. | Seed yield | 1000 seed weight | Oil concentration |
| Date of planting | 2 | 104539** | 11.215** | 61.538** | 3 | 40211** | 3.374** | 432.695** |
| Cultivar | 9 | 270243** | 128.583** | 898.136** | 9 | 67496** | 210.593** | 496.674** |
| Rep | 2 | 6150 | 1.020* | 9.914 | 2 | 5648* | 0.307 | 18.902 |
| Date of planting × cultivar | 18 | 47268 | 4.843** | 101.637* | 27 | 31934 | 4.858** | 171.517* |
| Error | 58 | 167040 | 6.506 | 174.158 | 78 | 84525 | 4.957 | 265.931 |
| Total | 89 | 595241 | 152.17 | 1245.38 | 119 | 229814 | 224.09 | 1385.72 |

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.

*Brasicus* species flowering could be estimated by the automated technique. Each species had a distinctive flowering pattern that could be used for species identification.

Peak flowering for a cultivar is represented by the peak in the percent of flower pixels for that cultivar (Fig. 4). In general, peak flowering decreased with later planting dates with the exception of R-500. Peak flowering and total flowering (Figs. 3 and 4) were not correlated with yield. The $r^2$ values for regressions of peak flowering for the rape cultivars against yield ranged from 0.09 for the 21 October planting date to 0.27 for 5 November planting date. The $r^2$ values for regression of total flowering against yield ranged from 0.03 for the 21 October planting date to 0.30 for the 5 November planting date.

Flowering parameters within a cultivar verses yield across planting dates were better correlated than flowering parameters across cultivars verses yield within planting dates. For peak flowering, the $r^2$ values ranged from 0.02 for Tobin to 0.64 for Hyola-029. For total flowering, the $r^2$ values ranged from 0.002 for Westar to 0.84 for crambe. When the correlations between yield and flowering were significant, the

Table 4
Planting dates, harvest dates, and seed yield of nine cultivars of rape and one cultivar of crambe grown during the 1995–1996 growing season

| Culivar | 3 November 1995 | | 24 November 1995 | | 15 December 1995 | | Mean |
|---|---|---|---|---|---|---|---|
| | Harvest date (1996) | Yield ($g\,m^{-2}$) | Harvest date (1996) | Yield ($g\,m^{-2}$) | Harvest date (1996) | Yield ($g\,m^{-2}$) | |
| Crambe | 24 April | 320 | 29 April | 242 | 30 April | 313 | 292[a] |
| *B. napus* cultivars | | | | | | | |
| A-112 | 24 April | 160 | 29 April | 138 | 30 April | 97 | 132 |
| Cyclone | 24 April | 199 | 29 April | 174 | 30 April | 117 | 163 |
| Oscar | 19 April | 231 | 29 April | 141 | 30 April | 151 | 174 |
| ST-011 | 22 April | 250 | 29 April | 132 | 30 April | 141 | 174 |
| Westar | 22 April | 207 | 29 April | 159 | 30 April | 156 | 174 |
| *B. rapus* cultivars | | | | | | | |
| CSU-045 | 19 April | 191 | 25 April | 141 | 30 April | 77 | 136 |
| Hyola-029 | 23 April | 283 | 25 April | 255 | 30 April | 149 | 229 |
| R-500 | 16 April | 340 | 22 April | 250 | 30 April | 217 | 269 |
| Tobin | 24 April | 145 | 25 April | 135 | 30 April | 91 | 124 |
| Mean | | 233[b] | | 177 | | 151 | |

[a] $LSD_{0.05}$ for cultivars is 51.
[b] $LSD_{0.05}$ for planting dates is 28.

slope of the regression was negative. This indicated that increased flowering did not necessarily lead to increased yield.

Four of the five methods used by Coffelt et al. (1989) to measure reproductive efficiency can be summarized as follows. If the reproductive output (total seed number or total seed weight or harvested yield) of a plant increases as total number of flowers decreases, then reproductive efficiency increases. Conversely, if reproductive output decreases as total number of flowers increases, then reproductive efficiency decreases. An unexpected finding of this study was that planting date affected the reproductive efficiency of these crops. Reproductive efficiency appeared to change with planting date because the highest total flowering and highest yields did not occur on the same planting date (Fig. 4 and Table 5). For example, the yield of A-112 for the 21 October 1997 planting date was 1262 kg ha$^{-1}$ and cumulative flower pixels were 13.5%, which was 93 kg ha$^{-1}$ per percent. For the 17 December 1997 planting date the yield of A-112 was 1684 kg ha$^{-1}$ and cumulative flower pixels were 10.0%, which was 168 kg ha$^{-1}$ per percent. The yield of A-112 per flower pixel was 80% higher for the 17 December 1997 planting date than for the 21 October 1997 planting date.

Overall, seed yields in 1995–1996 were higher than those in 1997–1998 for most cultivars and within years the planting date by cultivar interaction was not significant (Tables 3–5). The temperatures were lower in 1997–1998 than in 1995–1996. Generally, we observed more vegetative growth and lodging of the rape cultivars in 1997–1998 than in 1995–1996, which reduced the 1997–1998 yields. In 1997–1998, there were several dates when minimum temperatures were below 0 °C (Fig. 1). Crambe was damaged by frost in 1997–1998 resulting in smaller plants when flowering and seed set began and lower seed yields than in 1995–1996. Generally, the 5 November planting date had the highest yields except for ST-011, crambe, and Tobin, which yielded more at the 21 November planting date. Yields of the rape cultivars for the 21 October planting date were reduced because of lodging. Gross (1964) reported lodging in the earliest planting date for rape. The lodging appeared to be the result of excessive plant growth prior to the initiation of flowering. Plant heights in this study in excess of 1.5 m (Table 6) were 50% greater than those reported by Gross (1964)

Table 5
Planting dates, harvest dates, and seed yield of nine cultivars of rape and one cultivar of crambe grown during the 1997–1998 growing season

| Cultivar | 21 October 1997 | | 5 November 1997 | | 21 November 1997 | | 17 December 1997 | | Mean |
|---|---|---|---|---|---|---|---|---|---|
| | Harvest date (1998) | Yield ($g\,m^{-2}$) | Harvest date (1998) | Yield ($g\,m^{-2}$) | Harvest date (1998) | Yield ($g\,m^{-2}$) | Harvest date (1998) | Yield ($g\,m^{-2}$) | |
| Crambe | 14 April | 144 | 20 April | 177 | 30 April | 190 | 6 May | 179 | 173[a] |
| A-112 | 28 April | 126 | 29 April | 176 | 1 May | 151 | 12 May | 168 | 155 |
| Cyclone | 22 April | 157 | 29 April | 170 | 1 May | 146 | 12 May | 135 | 152 |
| Oscar | 28 April | 180 | 29 April | 221 | 30 April | 202 | 12 May | 109 | 178 |
| ST-011 | 23 April | 151 | 27 April | 108 | 30 April | 168 | 12 May | 161 | 162 |
| Westar | 22 April | 159 | 29 April | 195 | 30 April | 177 | 12 May | 143 | 169 |
| CSU-045 | 20 April | 87 | 23 April | 154 | 24 April | 143 | 1 May | 114 | 124 |
| Hyola-029 | 14 April | 141 | 27 April | 218 | 30 April | 179 | 6 May | 133 | 168 |
| R-500 | 6 April | 120 | 17 April | 186 | 24 April | 183 | 4 May | 154 | 161 |
| Tobin | 23 April | 63 | 23 April | 109 | 24 April | 115 | 1 May | 99 | 97 |
| Mean | | 133[b] | | 178 | | 165 | | 139 | |

[a] $LSD_{0.05}$ for cultivars is 27.
[b] $LSD_{0.05}$ for planting dates is 17.

Table 6
Heights (m) of rape and crambe cultivars at harvest in the 1995–1996 and 1997–1998 harvest years for each planting date

| | 1995–1996 | | | |
|---|---|---|---|---|
| | 3 November 1995 | 24 November 1995 | 15 December 1995 | |
| Crambe | 0.53 | 0.59 | 0.48 | |
| *B. napus* cultivars | | | | |
| A-112 | 1.33 | 1.38 | 1.22 | |
| Cyclone | 1.47 | 1.53 | 1.38 | |
| Oscar | 1.35 | 1.30 | 1.21 | |
| ST-011 | 1.66 | 1.47 | 1.35 | |
| Westar | 1.45 | 1.52 | 1.40 | |
| *B. rapus* cultivars | | | | |
| CSU-045 | 1.53 | 1.42 | 1.32 | |
| Hyola-029 | 1.48 | 1.39 | 1.34 | |
| R-500 | 1.40 | 1.18 | 1.17 | |
| Tobin | 1.54 | 1.30 | 1.24 | |
| | 1997–1998 | | | |
| | 21 October 1997 | 5 November 1997 | 21 November1997 | 17 December 1997 |
| Crambe | 0.70 | 0.81 | 0.66 | 0.62 |
| *B. napus* cultivars | | | | |
| A-112 | 1.45 | 1.54 | 1.29 | 1.36 |
| Cyclone | 2.02 | 1.86 | 1.68 | 1.37 |
| Oscar | 1.61 | 1.68 | 1.34 | 1.15 |
| ST-011 | 1.89 | 1.81 | 1.50 | 1.48 |
| Westar | 1.99 | 1.91 | 1.77 | 1.48 |
| *B. rapus* cultivars | | | | |
| CSU-045 | 1.93 | 1.79 | 1.72 | 1.43 |
| Hyola-029 | 1.34 | 1.80 | 1.53 | 1.26 |
| R-500 | 1.76 | 1.59 | 1.30 | 1.28 |
| Tobin | 1.76 | 1.81 | 1.62 | 1.34 |

and Johnson et al. (1995). Yields of spring planted rape and crambe are reduced when planting is delayed. Overall, yields were greater in previous reports (Gross, 1964; Johnson et al., 1995) than reported here. In this study, it is not clear whether this resulted from lower pollination rates, which could affect reproductive efficiency, less favorable environmental conditions, or other unknown factors.

Seed weights of rape tended to decrease with planting date whereas seed weights of crambe remained relatively unchanged (Tables 7 and 8). This resulted in a significant planting date by cultivar interaction (Table 3). In general, seed weights were higher for the November planting dates suggesting that there were more immature seeds in the October and December planting dates than the November planting dates in 1997–1998. These data suggest that seed development was affected by warm temperatures, for the December planting dates, which exceeded 30 °C periodically beginning in March of both years (Fig. 1). The seed weights were similar to those reported by Johnson et al. (1995) and follow the general trend of *B. napus* seed weights being greater than *B. rapus* seed weights.

Oil concentration of crambe was always lower than the rape cultivars (Tables 7 and 8). For the rape cultivars, those with the larger seed had higher oil contents. The planting date producing the maximum oil concentration varied among cultivars both years and resulted in a significant cultivar by planting date interaction (Table 3). No obvious patterns were observed with cultivars across years or species within years. The oil concentrations in this study were higher than those reported for spring plantings. Johnson et al. (1995) reported oil concentrations of rape from 280

Table 7
Seed weight and oil content of nine cultivars of rape and one cultivar of crambe grown at three planting dates during the 1995–1996 growing season

| Cultivar | 3 November 1995 | | 24 November 1995 | | 15 December 1995 | | Seed weight $LSD_{0.05}$ | Oil concentration $LSD_{0.05}$ |
|---|---|---|---|---|---|---|---|---|
| | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | | |
| Crambe | 5.9 | 364 | 5.5 | 338 | 6.0 | 395 | 1.0 | 87 |
| *B. napus* cultivars | | | | | | | | |
| A112 | 2.1 | 433 | 1.9 | 403 | 1.7 | 411 | 0.4 | 32 |
| Cyclone | 3.1 | 461 | 2.4 | 425 | 2.0 | 421 | 0.8 | 29 |
| Oscar | 2.6 | 440 | 2.3 | 415 | 2.1 | 418 | 1.1 | 65 |
| ST-011 | 4.3 | 492 | 3.3 | 458 | 2.8 | 481 | 0.6 | 23 |
| Westar | 4.1 | 484 | 3.1 | 451 | 2.6 | 448 | 0.8 | 30 |
| *B rapus* cultivars | | | | | | | | |
| CSU-045 | 2.0 | 454 | 1.9 | 457 | 1.3 | 441 | 0.6 | 34 |
| Hyola-029 | 3.7 | 472 | 3.0 | 449 | 2.7 | 460 | 0.6 | 14 |
| R-500 | 4.8 | 477 | 4.0 | 462 | 3.4 | 479 | 0.6 | 33 |
| Tobin | 1.9 | 450 | 1.8 | 464 | 1.5 | 458 | 0.7 | 40 |
| $LSD_{0.05}$ | 0.6 | 26 | 0.6 | 36 | 0.4 | 23 | | |

Table 8
Seed weight and oil content of nine cultivars of rape and one cultivar of crambe grown at four planting dates during the 1997–1998 growing season

| Cultivar | 21 October 1997 | | 5 November 1997 | | 21 November 1997 | | 17 December 1997 | | Seed weight $LSD_{0.05}$ | Oil content $LSD_{0.05}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | 1000 seed weight (g) | Oil concentration ($mg\,g^{-1}$) | | |
| Crambe | 6.9 | 440 | 6.7 | 484 | 7.0 | 450 | 7.5 | 377 | 0.3 | 26 |
| *B. napus* cultivars | | | | | | | | | | |
| A-112 | 2.6 | 488 | 3.3 | 509 | 2.5 | 468 | 2.3 | 427 | 0.4 | 48 |
| Cyclone | 3.3 | 504 | 3.7 | 506 | 3.1 | 495 | 2.7 | 448 | 0.4 | 37 |
| Oscar | 3.0 | 456 | 3.5 | 490 | 2.7 | 465 | 3.0 | 451 | 0.4 | 38 |
| ST-011 | 4.3 | 504 | 4.3 | 530 | 4.2 | 517 | 3.8 | 483 | 0.5 | 46 |
| Westar | 4.2 | 491 | 4.2 | 522 | 3.4 | 501 | 3.3 | 458 | 0.6 | 42 |
| *B. rapus* cultivars | | | | | | | | | | |
| CSU-045 | 2.3 | 474 | 2.3 | 495 | 2.1 | 496 | 1.9 | 459 | 0.2 | 17 |
| Hyola-029 | 3.3 | 482 | 4.0 | 507 | 3.3 | 501 | 3.2 | 480 | 0.6 | 23 |
| R-500 | 4.6 | 514 | 4.3 | 530 | 4.0 | 518 | 3.6 | 491 | 1.1 | 61 |
| Tobin | 2.2 | 472 | 2.4 | 489 | 2.1 | 515 | 2.1 | 477 | 0.3 | 29 |
| $LSD_{0.05}$ | 0.5 | 40 | 0.4 | 38 | 0.3 | 28 | 0.4 | 31 | | |

to 340 mg $g^{-1}$, whereas oil concentrations for rape in this study ranged from 403 to 509 mg $g^{-1}$. The differences cannot be attributed to cultivar effects because some of the same cultivars were grown in both studies. The oil concentration of crambe was also higher in this study by 100–200 mg $g^{-1}$ than that of Johnson et al. (1995) for the same cultivar. Even though seed yields of rape and crambe were in this study (Tables 4 and 5) were less than those reported by Johnson et al. (1995), the higher oil concentrations (Tables 7 and 8) in this study resulted in comparable oil yields to those reported by Johnson et al. (1995).

## 4. Conclusions

Water applications were lowest for the latest planting dates in both years. The time from planting to harvest was shortest for the latest planting date, which resulted in fewer irrigations. In 1997–1998, the 21 October planting date received the most irrigation because the growing season was longer than for the other planting dates.

Plant heights were greater than; oil concentrations were higher than; days to flowering were more than twice that of; seed yields were lower than; and seed weights and oil yields were comparable to spring planting in the Northern Great Plains. Oil concentration and 1000 seed weights decreased with later planting dates, suggesting less mature seed were harvested from the later planting dates. This study was not detailed enough to determine the physiological basis for the observed differences in plant growth and development. More study is needed of the mechanisms that are responsible for flower initiation, the end of vegetative growth, and reproductive efficiencies of these cultivars.

In both years of the study, the highest yields were achieved when rape and crambe were planted in November. This is adequate time following cotton harvest for most producers in the low deserts of the southwestern United States to prepare the field and plant a second crop. A high percentage of plants lodged resulting in lower seed yields. The increased lodging probably resulted in part from the extended period of growth prior to reproductive development compared with spring planting in Northern Great Plains. This was indicated by plant heights of 1.5 m for rape, which were much taller than reported elsewhere and resulted in a large volume of straw. Crambe was susceptible to frost and could only be grown in the most protected locations. In 1995–1996, only the CSU-045 and R-500 cultivars matured early enough to allow planting of cotton in mid- to late-April, which is the normal planting time in central Arizona. In 1997–1998, only the R-500 cultivar from the early November planting date was harvestable early enough to be used in a continuous cropping system.

Results from this study show that planting rape as a winter crop as part of a continuous cropping system in rotation with cotton in the low desert is feasible. However, for this system to produce maximum benefit, improved rape cultivars with less vegetative growth, earlier flowering and maturity, and higher yields are needed. In addition, frost tolerant cultivars of crambe are needed to make it a viable rotational crop with cotton in this system under the climatic conditions encountered.

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## References

Adamsen, F.J., Coffelt, T.A., Nelson, J.M., 2003. Flowering of lesquerella as affected by nitrogen fertilization and seeding rate. Ind. Crops Prod. 18, 125–131.

Adamsen, F.J., Coffelt, T.A., Nelson, J.M., Barnes, E.M., Rice, R.C., 2000. Method for using images from a color digital camera to estimate flower number. Crop Sci. 40, 704–709.

Busch, L., Gunter, V., Mentele, T., Tachikawa, M., Tanaka, K., 1994. Socializing nature: technoscience and the transformation of rapeseed into Canola. Crop Sci. 34, 607–614.

Coffelt, T.A., Seaton, M.L., VanScoyoc, S.W., 1989. Reproductive efficiency of 14 Virginia-type peanut cultivars. Crop Sci. 29, 1217–1220.

Fox, F.A., Jr., Slack, D.C., Clark, L.J., Scherer, T.F., 1993. AZSCHED-software for real-time irrigation scheduling. In: Allen, R.G. (Ed.), Management of Irrigation and Drainage

Systems: Integrated Perspectives, National Conference Proceedings on Irrigation and Drain. Eng., Park City, Utah, 21–23 July. Am. Soc. Civil Engineers, New York, NY, pp. 891–898.

Gross, A.T.H., 1964. Effect of date of planting on yield, plant height, flowering, and maturity of rape and turnip rape. Agron. J. 56, 76–78.

Johnson, B.L., McKay, K.R., Schneiter, A.A., Hanson, B.K., Schatz, B.G., 1995. Influence of planting date on canola and crambe production. J. Prod. Agric. 8, 594–599.

Kmec, P., Weiss, M.J., Milbrath, L.R., Schatz, B.G., Hanzel, J., Hanson, B.K., Eriksmoen, E.D., 1998. Growth analysis of crambe. Crop Sci. 38, 108–112.

Kondra, Z.P., 1977. Effect of date of planting on rapeseed. Can. J. Plant Sci. 57, 607–609.

Mahler, R.L., Guy, S.O., 2002. Northern Idaho Fertilizer Guide: Spring Canola. CIS 1012 (rev.). University of Idaho Extension, Idaho Agricultural Experiment Station, Moscow, Idaho.

Morrison, M.J., Stewart, D.W., 2002. Heat stress during flowering in summer brassica. Crop Sci. 42, 797–803.

Nelson, J.M., Dierig, D.A., Nakayama, F.S., 1996. Planting date and nitrogen fertilization effects on lesquellera production. Ind. Crops Prod. 5, 217–222.

SAS Institute, 1987. The GLM procedure. In: SAS/STAT Guide for Personal Computers. Version 6 ed. SAS Institute Inc., Cary, North Carolina, pp. 549–640.

Yitayew, M., Brown, P., 1990. Predicting daily evapotranspiration (ET) from short term values. J. Irrig. Drainage Eng. 116, 387–398.